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Tensile and Compressive Test on Thickness-Reduced Steel Plate Repaired by CFRP Strand Sheet and Underwater Epoxy with Bond Defects

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ABSTRACT

There are a significant number of marine steel structures suffering severe corrosion damage, and they are seriously in need of repair or strengthening to prevent structural failure. This study is focused on a repair technique using carbon fiber reinforced polymer (CFRP) sheet, especially, CFRP sheet bonding in the underwater environment. Underwater bonding of CFRP sheets is not yet a matured technique, and its repair performance for corroded steel structures is not fully understood. One of the issues is the effect of bond defects on the repair performance. Air bubbles are often found to be trapped in the adhesive layer. To examine an effect of bond defects on the repair performance, uniaxial loading tests are performed on thickness-reduced steel plates with CFRP strand sheets bonded by using underwater epoxy as adhesive. In total, sixteen CFRP strand sheet bonded steel plates are prepared, where test parameters are loading directions of tension and compression and the location of bond defects. The effect of bond defects on the repaired performance is examined in terms of yield strength, initial stiffness, and failure mode. As a result of experiment, it is found that two types of defects considered in this study do not affect repair performance significantly. However, when a CFRP bonded steel plate is under compression, buckling of CFRP strand sheet may control its compression strength, resulting in a smaller strength than the tensile strength.

KEYWORD

CFRP, steel plate, repair, bond defect, underwater

1. INTRODUCTION

There are a significant number of marine steel structures suffering severe corrosion damage, and they are seriously in need of repair or strengthening to prevent structural failure. The most common repair procedures for corrosion-damaged submerged structural steel components is the welding of steel patch plates in the underwater wet environment and the reinforced concrete patch repair over the corrosion-damaged areas [1].

In this study, examined is a repair technique using carbon fiber reinforced polymer (CFRP) sheet, especially, CFRP sheet bonding in the underwater environment. CFRP bonding repair for steel structures have been studied in the last decade by various researchers [2-5]. More recently, underwater bonding technique has been examined by a few researchers [6-7]. CFRP sheet underwater bonding repair for corroded steel structures has various advantages over conventional repair techniques. First of all, CFRP has high corrosion resistance. As long as the bonding between steel and CFRP is sound, substrate steel is protected for corrosion. Secondly, because CFRP sheet is lightweight, the repair work does not require heavy machines. Finally, since the technique does not require a dry chamber around the portion to be repaired, a repair cost can be inexpensive, and a working time can be much reduced.

However, underwater bonding of CFRP sheets is not yet a matured technique, and its repair performance for corroded steel structures is not fully understood. One of the issues is the effect of bond defects on the repair performance. Since adhesive for underwater bonding has high viscosity, the technique is susceptible to air bubbles trapped in the layer of adhesive. CFRP strand sheets used in Ref [7] was developed to reduce such bond defects by letting air bubbles and water easily escape through spaces between strands. However, underwater bonding of CFRP strand sheets on steel structures is not totally free from bond defects depending on the type of adhesive and skills of workers.

To understand the effect of bond defects in the CFRP bonding repair on the repaired performance, this study examines the mechanical behavior of CFRP strand sheet bonded steel plates with bond defects under uniaxial tension and compression experimentally. Performance recovery is examined

in terms of stiffness, strength, and failure modes.

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

The configuration of CFRP bonded steel plates used in this study is shown in Fig. 1. A steel plate of 50 x 440 x 19 mm has a uniform thickness reduction of 2 mm for a length of 20 mm at the center of the plate on both sides. After surfaces of a steel plate with a thickness-reduced portion is prepared by sand-blasting, a CFRP strand sheet is bonded in the underwater environment by using underwater epoxy to cover the thickness reduced section. The total length of CFRP strand sheet is 240 mm, resulting in a bond length of 100 mm on each side.

Two types of bond defects are introduced in the specimen as shown in Fig. 2. In Type A, an unbonded area corresponds to the thickness-reduced portion. In Type B, an unbonded area for a length of 20 mm is provided at the location 20 mm away from the edge of

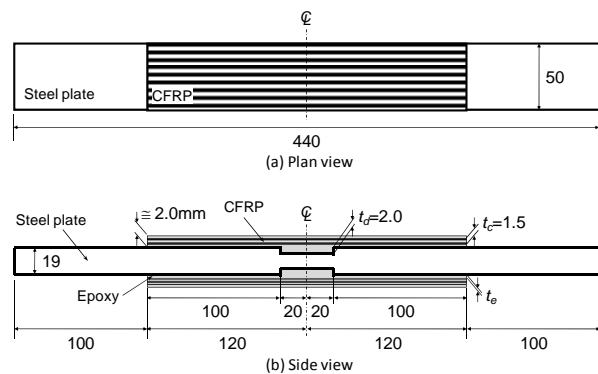


Fig. 1 Configuration of test specimen (unit: mm)

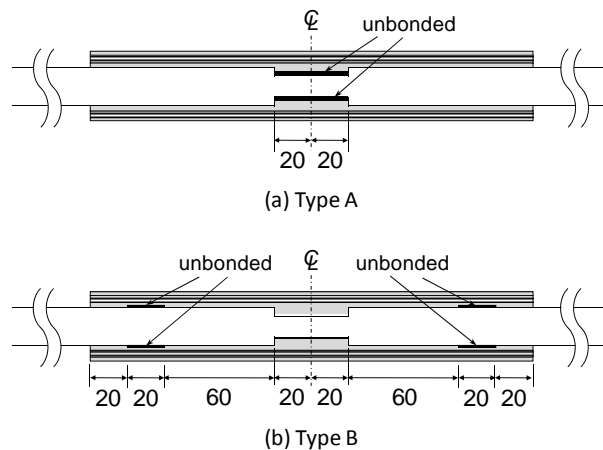


Fig. 2 Bond defects (unit: mm)



(a) Application of epoxy on steel



(b) CFRP strand sheet placement



(c) Surface sealing layer of epoxy

Fig. 3 Specimen fabrication procedure

CFRP. In both Type A and Type B, CFRP is unbonded for the whole specimen width in each defect.

Fig. 3 shows a fabrication procedure of the CFRP bonded specimens in this study. Firstly, epoxy adhesive is spread on the steel plate underwater, and the epoxy is also applied to the portion where steel thickness is reduced. Secondly, a CFRP strand sheet is placed on the epoxy layer. Finally, epoxy is spread over the CFRP strand sheet as a surface sealing layer. A target total thickness of CFRP strand sheet and epoxy layers is 2 mm, resulting in an average thickness of each epoxy layer of 0.25 mm considering a diameter of a CFRP strand is 1.5 mm. The specimens were submerged underwater for forty-eight hours to cure the epoxy, and then they were taken out from the water and were kept in air at ambient temperature until the test. Water temperature at the time of specimen fabrication was 22°C.

To create unbonded regions, nylon tape of the size of defect was attached on the steel plate so that epoxy to be spread on the tape would not bond CFRP and steel.

Table 1 Test specimens in this study

Name	CFRP repair	Loading direction	Defect type	# of specimens
L0T	No	Tension	None	2
L0C	No	Compression	None	2
L1TA	Yes	Tension	A	4
L1CA	Yes	Compression	A	4
L1TB	Yes	Tension	B	4
L1CB	Yes	Compression	B	4

Table 1 lists all specimens tested in this study. All CFRP bonded specimens have one layer of CFRP strand sheet on each side. In addition to CFRP bonded specimens, steel plates with a 2-mm thickness reduction were also tested as listed in Table 1.

2.2 Materials

(1) Steel

The grade of steel plate is SM490A, which is specified in Japanese Industry Standard (JIS) G3106. Tensile test of steel coupons from the steel plate found Young's modulus E_s of 211 GPa, yield stress σ_{sy} of 343 MPa, and tensile strength σ_{st} of 498 MPa.

(2) CFRP strand sheet

The CFRP strand sheet is formed from CFRP strands each with a nominal diameter of $d_c=1.5$ mm, and strands are spaced properly and further aligned into a sheet form using transverse threads for ease of handling and deployment. The manufacturer's catalog for the CFRP strand sheet provides Young's modulus E_c of 640 GPa, the tensile strength σ_{ct} of 1,900 MPa, and the design thickness t_{cd} of 0.429 mm. The fiber volume fraction in the form of strand sheet is calculated to be $V_f = t_{cd}/d_c = 0.286$, and that of each strand is $V_f' = 0.465$.

(3) Underwater epoxy

Epoxy adhesive used in the specimens is currently used for underwater structures as a corrosion preventive coating. The epoxy has high viscosity so that it will not flow down during the spreading in the water. Tensile tests of epoxy coupons were conducted by following the procedure specified in JIS K7113, at different curing times of 21, 65, 175, and 250 days, under a displacement control at a rate of 0.015 mm/sec. The nominal width and thickness of epoxy coupons in the test region were 10 mm and 4 mm, respectively. Fig. 4 shows representative tensile test curves, and results from the different curing times are summarized in Fig. 5. In Fig. 5, E_e , σ_{et} , and ε_{em} are Young's modulus,

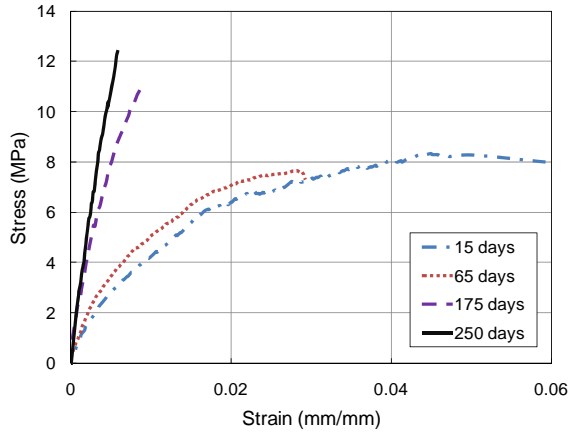


Fig. 4 Tensile test curves for epoxy coupons

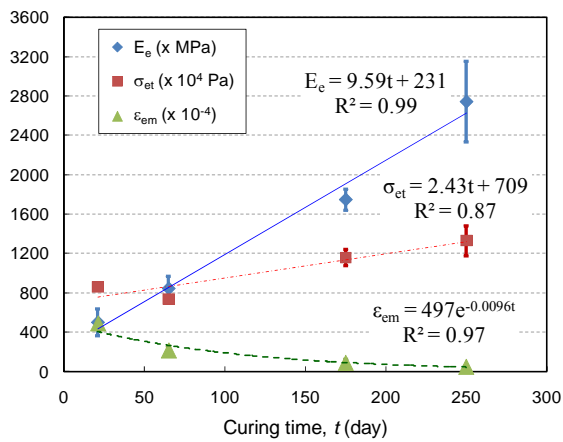


Fig. 5 Curing effect of epoxy properties

tensile strength, and the strain at the tensile strength of epoxy coupons, respectively.

It is found that after 20 days of curing, the Young's modulus of epoxy has a mean value of only about 0.5 GPa, which is much smaller than the typical value of epoxy. In Fig. 5, regression curves based on test results are also plotted. Both Young's modulus and tensile strength are found to increase linearly with time, while the strain at tensile strength tends to decrease exponentially with time. The epoxy used in this study shows a very slow curing process, and its properties continue to change up to at least 250 days. Since CFRP bonded specimens were tested 116 to 146 days after fabrication, Young's modulus of epoxy is expected to vary from 1.3 GPa to 1.6 GPa, if the curing conditions of test specimens are the same as in epoxy test coupons.

2.3 Test Setup

Test specimens were subjected to either monotonic tension or compression by using a 500 kN MTS



Fig. 6 Test setup

Table 2 Dimensions and material properties used in the analytical solution

<i>Steel</i>	
Plate thickness (mm)	18.6
Thickness reduction on each side (mm)	14.5
Young's modulus (GPa)	211
<i>Epoxy</i>	
Shear modulus (GPa)	0.55
Thickness between CFRP and steel (mm)	0.7
<i>CFRP</i>	
Young's modulus* (GPa)	183
Thickness (mm)	1.5

*This is equivalent Young's modulus for 1.5 mm thick CFRP layer.

material testing machine under a displacement control. Applied load, strains of CFRP and steel, and relative displacement between CFRP and steel plate at the edge of CFRP sheet were measured during the test. The test setup is shown in Fig. 6.

3. ANALYTICAL SOLUTION

Based on the analytical derivations in Refs [8] and [9], normal stresses in the steel plate and the CFRP strand sheet in the loading direction and shear stress in epoxy adhesive can be derived for both Type A and Type B specimens. In this section, stress distributions calculated for Type A and Type B specimens are compared to those in the CFRP bonded steel plate without any defect.

3.1 Assumptions

Dimensions and material properties used to calculate stress distributions are listed in Table 2. In lieu of considering CFRP strands, a

homogeneous plate with Young's modulus of 183 GPa and a thickness of 1.5 mm is assumed to be bonded on a steel plate. Other necessary dimensions are from Figs. 1 and 2. All materials are assumed to be linearly elastic. Specimens are subjected to a tensile loading, where normal stress at the end of the steel plate is σ_{sn} .

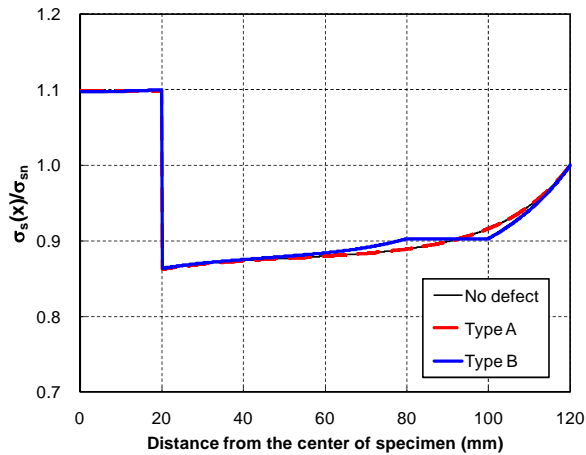


Fig. 7 Analytical solution: stress in steel plate

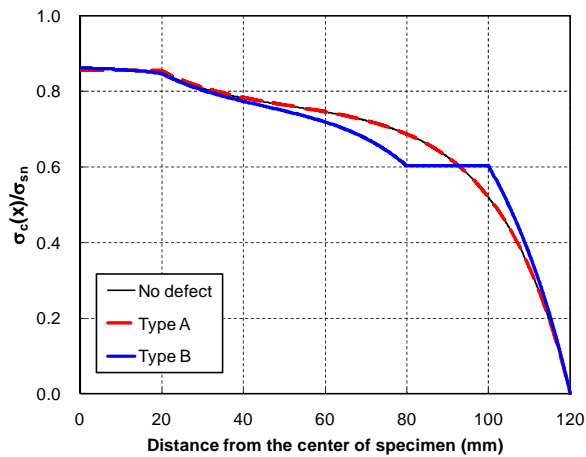


Fig. 8 Analytical solution: stress in CFRP

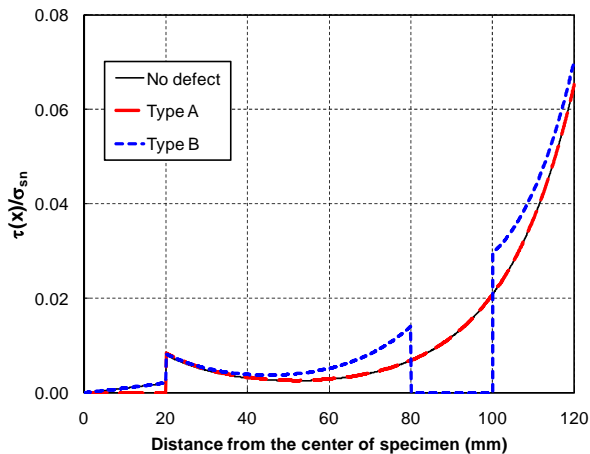


Fig. 9 Analytical solution: shear stress in epoxy

3.2 Stress and Strain Distributions

Analytical solutions for steel stress, CFRP stress, and shear stress in epoxy are shown in Fig. 7 to Fig. 9, respectively. Stresses in these plots are normalized by the steel stress at the end of plate, σ_{sn} . The horizontal axis shows the distance from the center of specimen; the center of the thickness-reduced portion is located at 0 mm, and CFRP bonding ends at 120 mm. In addition to specimens with Type A and Type B defects, the case without defect is also calculated for comparison.

As can be seen in these figures, there is insignificant difference between the no defect and Type A defect cases. For Type B defect, there is about 8% increase of shear stress at the end of CFRP sheet; however, steel stress at the thickness-reduced portion is not affected by the Type B defect. Therefore, based on analytical solutions, Type A and Type B defects considered in this study do not affect repair performance under tension.

In the next section, strength of specimens with defects is examined in terms of loading directions.

4. TEST RESULTS AND DISCUSSIONS

In this section, test results are summarized. Based on the test results, the effect of defects and loading directions on the repair performance is discussed.

4.1 Observed Failure Modes

Observed failure modes are summarized in Table 3. Regardless of the defect type, specimens under tension yielded at the thickness-reduced portion first, followed by debonding of CFRP strand sheets at their ends, except for one specimen, L1TA-3. The specimen L1TA-3 showed CFRP tension failure after yielding of steel. Since overall strength of L1TA-3 was not very different from the other tension specimens, CFRP strand sheets in the other tension specimens may have been close to failure when debonding occurred.

Specimens under compression always showed buckling of CFRP strand sheet first, followed by yielding of steel at the thickness-reduced portion and global buckling, regardless of the defect type. Fig. 10 shows CFRP strains of 7 locations against applied load. Measurement locations are: $x=0, 20, 50, 80, 95, 105, 115$ mm, where the x coordinate is originated from the center of the specimen towards the end of CFRP sheet. As can be seen in the

Table 3 Failure modes

Specimen	Failure mode
L1TA-1	Yielding of steel → CFRP debonding
L1TA-2	Yielding of steel → CFRP debonding
L1TA-3	Yielding of steel → CFRP failure
L1TA-4	Yielding of steel → CFRP debonding
L1CA-1	CFRP buckling → yielding of steel
L1CA-2	CFRP buckling → yielding of steel
L1CA-3	CFRP buckling → yielding of steel
L1CA-4	CFRP buckling → yielding of steel
L1TB-1	Yielding of steel → CFRP debonding
L1TB-2	Yielding of steel → CFRP debonding
L1TB-3	Yielding of steel → CFRP debonding
L1TB-4	Yielding of steel → CFRP debonding
L1CB-1	CFRP buckling → yielding of steel
L1CB-2	CFRP buckling → yielding of steel
L1CB-3	CFRP buckling → yielding of steel
L1CB-4	CFRP buckling → yielding of steel

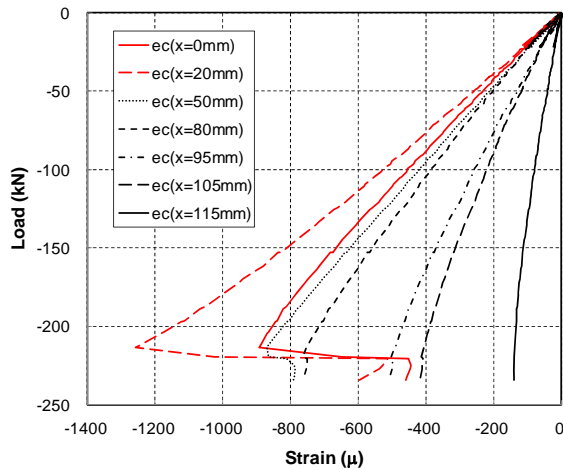


Fig. 10 CFRP strains vs. Load (L1CA-2)

figure, at $x=20$ mm, at the edge of thickness-reduced section, the CFRP strain is the maximum and larger than that of $x=0$ mm, the center of the specimen. This phenomenon was caused by additional bending moment in the CFRP sheet at the thickness-reduced portion. When CFRP sheet tends to bulge out at the center of specimen, the bending moment causes CFRP strain of the outer surface at the center to decrease, and CFRP strain of the outer surface at the edge of thickness-reduced section to increase.

By examining CFRP strains of all compression specimens, it was found that CFRP strand sheet buckled at the strain of $1,100 \mu$ to $1,300 \mu$. The measured strain at the initiation of buckling did not differ significantly between Type A and Type B defects. By using CFRP properties shown in

Table 2 and assuming an unsupported length equal to the length of thickness-reduced portion, 40 mm, the buckling strain of a CFRP sheet can be calculated as $1,160 \mu$. Since Type B specimens showed similar buckling strains, a thick epoxy layer in the thickness-reduced portion may not have a significant contribution to the buckling strength, which will have to be examined in detail in the future.

4.3 Comparison with Analytical Solutions

Figs. 11 and 12 show steel and CFRP strains measured along the test specimens when steel stress at the end of plate $\sigma_{sn}=100$ MPa. For comparison, analytical solutions discussed in Section 3 are also plotted. Horizontal axis shows a distance from the center of the specimen. In these figures, strains are normalized by the steel strain at the end of plate, ϵ_{sn} .

For both steel and CFRP, measured strains capture

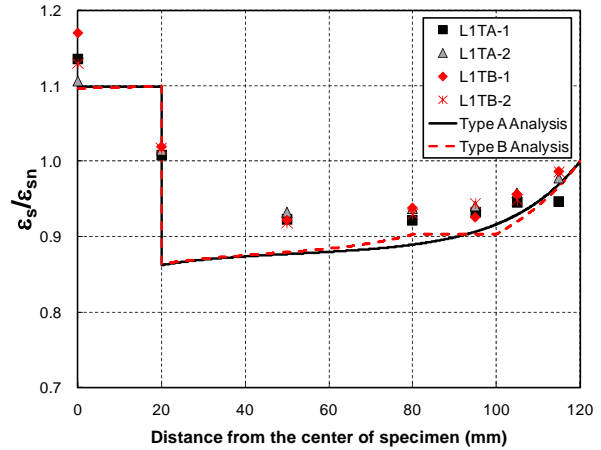


Fig. 11 Steel strain distributions

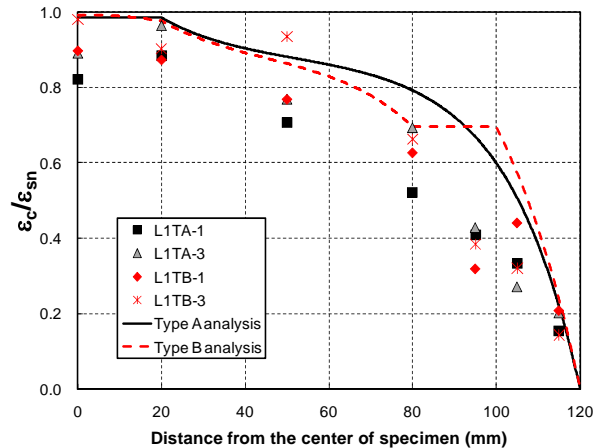


Fig. 12 CFRP strain distribution

the trends of strain distributions from the analytical solution. However, measured steel strains are larger, and measured CFRP strains are smaller than the analytical solution, implying that the current analytical solution overestimates the actual repair performance of CFRP bonding. One of the possible causes of this overestimation is a modeling assumption for CFRP strand sheet described in Section 3.1.

4.2 Stiffness and Strength Comparison

To compare performance recovery due to CFRP bonding among different specimens, initial stiffness and strength are examined. The initial stiffness is defined as 0.7 times the yielding load of each specimen divided by the corresponding steel strain at the thickness-reduced portion of specimen. As a strength value, yielding load was obtained as a 0.2% offset value based on the steel strain at the thickness-reduced portion.

Figs. 13 and 14 show initial stiffness and yielding load comparisons, respectively. In each figure, values are normalized by a corresponding value for an intact steel plate that does not have a thickness reduction. Average values and standard deviations of the test results from the same set of specimens are plotted in the figure.

In the design calculation, the stiffness provided by one CFRP layer is equivalent to that provided by a 1.3 mm thick steel plate. Therefore, the CFRP bonded steel plates with a thickness reduction of 2 mm on two sides are expected to recover its stiffness up to about 92% of the stiffness of an 18.6 mm thick intact steel plate. This value is shown as a dashed line in both figures.

Although stiffness increased due to CFRP bonding repair for both defect types when compared to that of specimens without CFRP, it did not reach the design value as can be seen in Fig. 13, which is the same finding as that discussed in Section 4.3. In terms of the type of defect, the obtained stiffness did not differ significantly between two types of defects. However, compression specimens showed a slightly higher stiffness than tension specimens. Although at the time of writing, the reason is not fully understood, the effect of epoxy curing may play a certain role because the compression specimens were tested about two weeks after the tension specimens.

Yielding load was recovered better than stiffness for tension specimens. For both Type A and Type

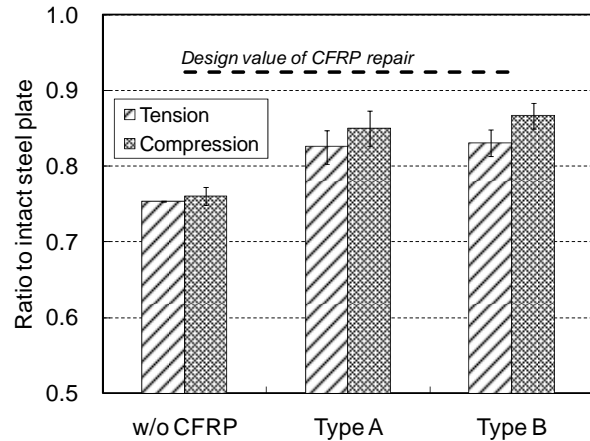


Fig. 13 Stiffness comparison

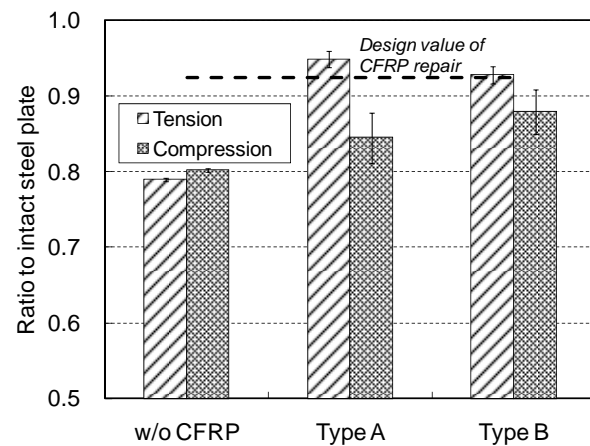


Fig. 14 Yielding load comparison

B specimens under tension, yielding load recovered to the repair design level. The larger recovery effect for yielding load in the tension specimens than stiffness may be caused by the nonlinearity of stress-strain relationship of epoxy as shown in Fig. 4. Due to the nonlinearity, the shear stress distribution becomes more uniform along the length of plate at yielding of steel than the case where steel is well under yield stress.

However, yielding load for compression specimens did not recover as well as tension specimens. This is due to CFRP buckling prior to yielding of steel. Since Type A specimens have defect at the thickness-reduced portion for a length of 40 mm, the yielding load became slightly smaller than that of Type B specimens. Results suggest that when CFRP strand sheets are bonded to compression members, buckling strength of CFRP strand sheet needs to be carefully considered in the design.

As analytical solutions discussed in Section 3

already suggested, two types of defects considered in this study did not affect repair performance in terms of initial stiffness and strength when a CFRP bonded plate is in tension.

5. CONCLUSIONS

In this study, uniaxial loading tests were performed on thickness-reduced steel plates with CFRP strand sheets bonded by using underwater epoxy as adhesive to examine an effect of bond defects on the repair performance. Test parameters were loading directions of tension and compression and the location of bond defects. The effect of bond defects on the repaired performance was examined in terms of yield strength, initial stiffness, failure mode. Conclusions from this study can be summarized as follows.

- (1) Based on the analytical solution of stress distributions in a CFRP bonded thickness-reduced steel plate with bond defects, two types of defects examined in this study do not affect the stiffness recovery significantly. However, when the bond defect is located near the ends of CFRP sheet, shear stress in the adhesive becomes higher, which may result in a premature debonding.
- (2) The uniaxial loading tests also showed stiffness after repair did not differ significantly for loading directions of tension and compression and for Type A and Type B defects considered in this study. However, achieved stiffness did not reach the repair design stiffness, and was about 91% of the repair design value.
- (3) Yielding loads of the tension specimens were higher than the design value although the specimens had bond defects.
- (4) Yielding loads in compression were smaller than those in tension due to buckling of CFRP strand sheets prior to the yielding of steel.

To apply the underwater CFRP bonding technique to repair actual corroded steel structures, a higher stiffness recovery rate is desired, and compression strength of CFRP bonded steel with different degrees of corrosion will have to be clearly understood in the future.

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